A Portable Low-Power Harmonic Radar System and Conformal Tag for Insect Tracking

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***Abstract*—Harmonic radar systems provide an effective modality for tracking insect behavior. This letter presents a harmonic radar system proposed to track the migration of the Emerald Ash Borer (EAB). The system offers a unique combination of portability, low power and small tag design. It is comprised of a compact radar unit and a passive RF tag for mounting on the insect. The radar unit transmits a 5.9–6 GHz signal and detects at the 11.8–12 GHz band. A prototype of the radar unit was built and tested, and a new small tag was designed for the application. The new tag offers improved harmonic conversion efficiency and much smaller size as compared to previous harmonic radar systems for tracking insects. Unlike RFID detectors whose sensitivity allows detection up to a few meters, the developed radar can detect a tagged insect up to 58 m (190 ft).**

***Index Terms*—Harmonic radar, insect tracking, radar, radio frequency identification (RFID).**

I. INTRODUCTION

HARMONIC radars have been used to track insects for 20 years [1]–[9]. However, existing radars either use low frequencies not suited for small tags or transmit high power (tens of kilowatts) severely limiting portability, so the successful tracking rate is very low. This letter presents an insect radar system that offers a combination of portability, low-power operation, and tag miniaturization not currently available in modern insect radars. The motivation is to allow the tracking of the Emerald Ash Borer (EAB), an exotic beetle native to Asia. EAB has caused tens of millions of dollars damage to ash trees in North America since 2002. The dispersal and behavioral patterns of EAB are needed to aid development of appropriate treatment and management strategies. Tracking EAB is an essential part of dispersal and behavioral studies.

The proposed harmonic radar relies on a small radio frequency (RF) tag attached to a captured and released insect. The system's unique features are portability, low power operation, and small tag design, coupled with a remarkably large detection distance. Specifically, the prototype was shown to track the small RF tag up to a range of approximately 58 m (190 ft). The radar is powered by a 12 V alarm battery and is compact enough (excluding the antennas) to be placed in a small backpack. Compared to units with output powers on the order of tens of kilowatts [1]–[4], this radar's output power is quite low (approximately 0.1 W). It operates at 5.9–6/11.8–12 GHz and employs a geometrically miniaturized RF tag. The tag measures 9.5 mm × 9.5 mm, or $0.19\,\lambda_0 \times 0.19\lambda_0$ at the system transmit frequency. Unlike loop-dipole tags previously used in this application [3]–[5], the proposed tag is conformal to the insect's body.

II. RADAR SUBSYSTEM

The radar tracking system is comprised of two components: the radar unit and the RF tag. The radar unit transmits a 5.9–6 GHz signal and detects the 11.8–12 GHz harmonic created by the tag. A system schematic is depicted in Fig. 1 and a photograph of the prototype system is given in Fig. 2, all built with commercially available parts. As shown, to generate the 5.9–6-GHz transmit signal, the output of a 5-GHz dielectric resonator oscillator (DRO) and the output of a stable 0.9–1 GHz auxiliary oscillator are mixed. The prototype system exhibited similar performance when the auxiliary oscillator frequency was 0.9 GHz and when the oscillator frequency was 1.0 GHz. It was found necessary that the transmit signal be sufficiently filtered to remove harmonics, as false positive detection scenarios can occur if the harmonic is transmitted. The received 11.8–12 GHz signal must also be filtered prior to amplification to remove any coupled or reflected transmitted (5.9–6 GHz) signal. That is, if the transmit signal is amplified in the receive circuit, it can create harmonics, resulting in false positive detections.

Detection occurs at 1.8–2.0 GHz. A 10-GHz signal is mixed with the received signal to generate the observed (1.8–2 GHz) IF signal. It should be noted that the harmonic of the 5 GHz DRO is isolated and amplified to generate the 10 GHz signal. The two circuits (5 and 10 GHz) are separated with a Wilkinson power divider. This design ensures that the observed IF is stable in spite of any frequency drift exhibited by the DRO, and also eliminates the need for another oscillator. The observed IF signal can be detected with a spectrum analyzer, RFID detection system or RF signal detection chip (such as the Analog Devices AD608).

Electromagnetic interference considerations are critical to a successful design as internal harmonics of the auxiliary oscillator signal or the transmit signal can allow the system to register false detections. To eliminate such issues, the low noise block, auxiliary oscillator, and the rest of the system were placed in three separate, tightly sealed boxes (see Fig. 2). Also, the buffer in the transmit circuit must provide sufficient isolation so that the auxiliary oscillator and/or transmit signals do not leak into the receive circuit through the DRO or power divider.

A power budget analysis for the radar system is given in Table I. In the analysis, it is assumed that the radar detects the

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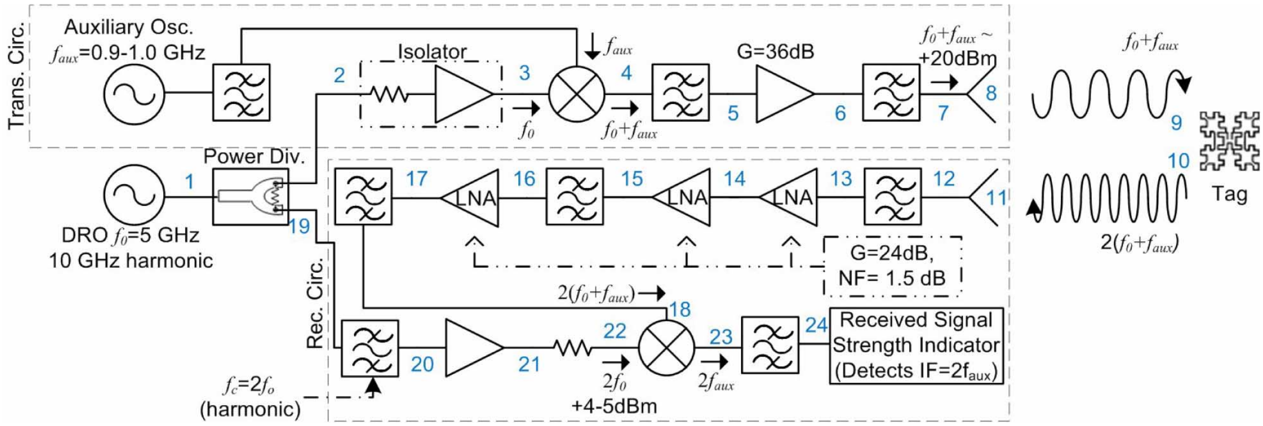

Fig. 1. Schematic of the insect radar system. The 5 GHz signal and 10 GHz signal originate in the same (nominally 5 GHz) oscillator, using the oscillator's first harmonic. The node numbers mark points referred to in Table I, the system power budget analysis.

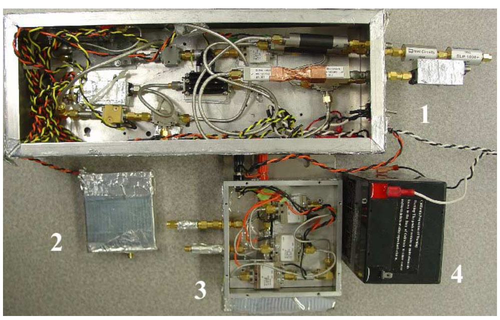

Fig. 2. Radar subsystem prototype (antennas and RSSI not pictured). As pictured: 1) transmitter and mixing circuit, 2) 1 GHz oscillator, 3) low-noise block, and 4) 12 V alarm battery.

tag at a range of 58 m (190 ft), and received power at a point in the system is given by

$$P_{\rm REC} = P_T - L_P - L_{\rm CONV} + \sum G \quad [\rm dB] \qquad (1)$$

where P_T is transmitted power, L_P is path loss, L_{CONV} is tag conversion loss (taken to be 11 dB, as discussed in a later section), and G is a component's gain or loss. At a given point, the summation of preceding component gains is considered. L_P and L_{CONV} are, of course, considered to be zero in (1) at points before their respective encounters (nodes 1–8 for L_P, nodes 1–9 for L_{CONV}). Noise power at a point in the system is given by

$$P_N = N_0 + \sum \rm NF \quad [dB] \qquad (2)$$

where N_0 is the thermal noise in the system at the point before the first active component and NF is a component's noise figure. A summation of preceding component noise figures is considered. Thermal noise is given by

$$N_0 = kTB \qquad (3)$$

where k is Boltzmann's Constant, T is ambient temperature, and B is bandwidth. The latter is assumed 30 Hz, as this was the resolution setting of the spectrum analyzer used in the experiments. The table shows two scenarios in determining the power at a given point: one where ideal (free space) path loss (FSPL) is assumed so that

$$L_P = \left(\frac{4\pi d}{\lambda}\right)^2 \qquad (4)$$

and another where an empirical path loss (EPL, derived via power regression of the experimental data presented in Fig. 9) that accounts for ground reflection is assumed so that

$$L_P = \left(\frac{4\pi}{\lambda}\right)^2 d^{5.707/2}. \qquad (5)$$

TABLE I
THEORETICAL SYSTEM POWER BUDGET ANALYSIS

Node[a]	Freq. (GHz)	Power (dBm) FSPL[b]	Power (dBm) EPL[c]	Noise (dBm)	SNR (dB) FSPL[b]	SNR (dB) EPL[c]
1	5.0	15.8				
2	5.0	12.8				
3	5.0	12.3				
4	5.9	-13.4				
5	5.9	-15.4				
6	5.9	20.6				
7	5.9	20.1 **(21.7)**				
8	5.9	42.1				
9	5.9	-41.0	-56.1			
10	11.8	-52.0	-67.1			
11	11.8	-141.1	-171.2			
12	11.8	-119.1	-149.2			
13	11.8	-122.1	-152.2	-159.2	34.8	7.0
14	11.8	-98.1	-128.2	-133.7	31.8	5.5
15	11.8	-74.1	-104.2	-108.2	30.3	4.0
16	11.8	-75.1	-105.2	-109.2	28.8	4.0
17	11.8	-51.1	-81.2	-83.7	28.8	2.5
18	11.8	-52.1	-82.2	-84.7	27.3	2.5
19	10.0	-15.2	-15.2			
20	10.0	-17.1	-17.1			
21	10.0	6.9	6.9			
22	10.0	3.9	3.9			
23	1.8	-61.1	-91.2	-93.7	27.3	2.5
24	1.8	-62.6	-92.7 **(-90)**	-95.2		2.5

[a]Nodes refer to marked points on Fig. 1, system schematic.
[b]Free space path loss assumed.
[c]Empirical path loss: assumed to behave as indicated by (5).
[b,c]Range assumed to be 58 meters (190 feet). Numbers in bold are measured values.

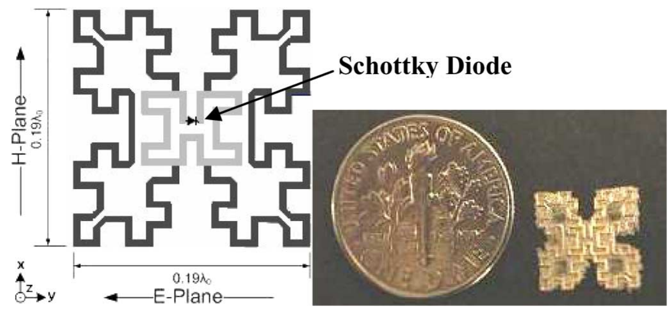

Fig. 3. The modified Minkowski loop tag is composed of two concentric fractal loops. At $f_0 = 5.91$ GHz, the tag measures 9.5 mm × 9.5 mm.

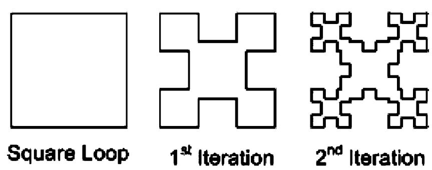

Fig. 4. Formation of a Minkowski loop [10].

III. Tag Design

A. Geometry

The proposed tag is a planar geometry (that is easily bent) comprised of two concentric (modified) Minkowski loops (see Fig. 3). The Minkowski loop is a fractal geometry which is refined iteratively as shown in Fig. 4. The Minkowski loop antenna has been shown to be a suitable miniaturized alternative to the square loop antenna [10]–[13]. Unlike the antennas in [11], [12], the proposed tag employs a set of modified Minkowski loops. These loops were altered to meet the fabrication constraints imposed by the tag's smaller size (due to higher operational frequencies). A similar alteration was made in [13], for a fractal-based slot antenna. The design measures 9.5 mm × 9.5 mm, or $0.19\lambda_0 \times 0.19\lambda_0$ at $f_0 = 5.91$ GHz.

B. Tag Operation and Diode Considerations

The tag intercepts the transmitted signal from the radar unit (5.9–6 GHz) and reradiates the harmonic at 11.8–12 GHz. As in other harmonic radar tags [14], a very small and light (low barrier) Schottky diode is positioned between the two loops as shown in Fig. 3. As the antenna is excited by the impinging radar wave, a current is induced through the diode which (due to its non-linearity) creates the re-radiated harmonic. Given the size and weight requirements of this application, the Avago/Agilent HSCH-5340 was found as a suitable diode for the tag. Schottky diodes, such as this one, operate with a low forward voltage drop. This is critical for the application, since the expected induced voltage is very small.

C. Tag Performance

The simulated gain patterns of the tag are given in Fig. 6–8. The disparity in gain between the co-polarization patterns and the cross-polarization patterns demonstrates the antenna's strong linear polarization. The maximum low mode gain is about 2.8 dBi (see Fig. 5), whereas the maximum high mode gain is about 5.5 dBi (see Fig. 6). However, the low- and high-mode maximum gain points do not occur in the same

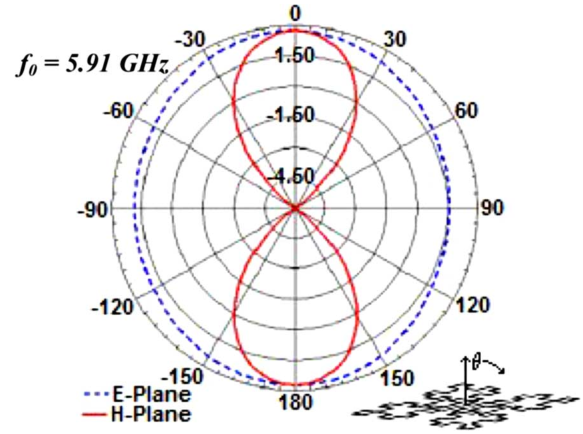

Fig. 5. Copolarization elevation angle gain pattern of the modified Minkowski loop at 5.91 GHz.

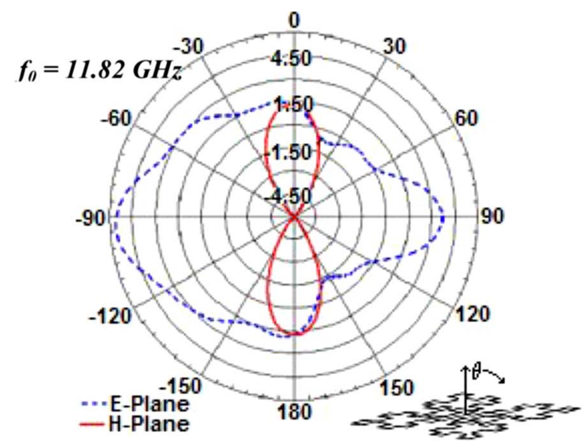

Fig. 6. Copolarization elevation angle gain pattern of the modified Minkowski loop at 11.82 GHz.

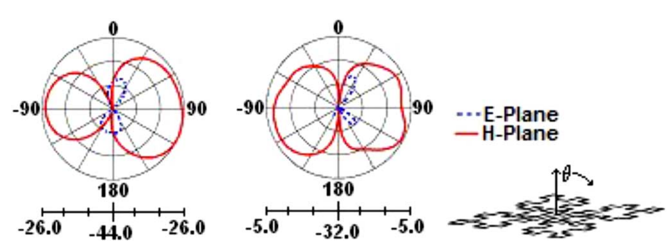

Fig. 7. Cross-polarization elevation angle gain patterns of the modified Minkowski loop at 5.91 GHz (left) and 11.82 GHz (right).

direction. In testing, the tag surface was placed normal to the direction of incidence (direction of maximum low mode gain).

The approximate conversion loss of the modified Minkowski loop tag was measured to be 11 dB at 5.91/11.82 GHz. This conversion loss corresponds to the power differential between an incident signal and the resulting re-radiated signal. This is an improvement over the loop-dipole tag, a resonant tag shown in Fig. 8, previously used in harmonic radars for insect tracking [3]–[5]. The improvement is significant since a tag with lower conversion loss is capable of a longer detection range. A loop-dipole tag, which consists of a half wavelength dipole for the low mode and a single wavelength loop for the high mode, was built and the conversion loss was measured as 16 dB. Also, in

Fig. 8. Loop dipole tag, previously used in harmonic insect radar systems [4]. The new Minkowski loop tag exhibits improvements in size, gain, conversion efficiency, and conformability.

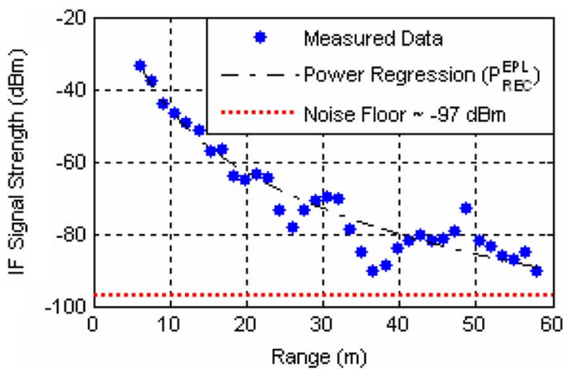

Fig. 9. IF signal strength (signal observed by the "Received Signal Strength Indicator," as shown in Fig. 1). Measurements taken at 1.83 GHz (auxiliary oscillator frequency was 915 MHz).

another insect radar system study (where a loop-dipole tag was used), the conversion loss was reported as 21 dB [3]. The modified Minkowski loop tag offers improvements in size, gain, conversion efficiency, and conformability.

IV. Experimental Results

Range measurements were conducted using a prototype radar unit. The IF signal, viz., the signal fed into the "Received Signal Strength Indicator" shown in Fig. 1, was measured as a Minkowski loop tag (shown in Fig. 3) was moved to varying ranges from the transmitting radar unit's antennas. The experiment was conducted outdoors in a flat, dry field. The system was operating at $5.915/11.830$ GHz and the RF power output was measured to be approximately $+20$ dBm. The transmit and receive antennas, both horns with gains of approximately 22 dBi at the respective relevant frequencies, were placed about 5 ft above the ground. Also, the tag was placed on a thin layer of foam and mounted atop a wooden stand 5 ft above the ground. The IF strength measurements were performed with a spectrum analyzer, where (two point) averaging was employed and the resolution bandwidth was set to 30 Hz, producing a noise floor of approximately -97 dBm (caused by amplification in the receive circuit).

The measurement results given in Fig. 9 show that the system was able to reliably detect the Minkowski loop tag up to a range of 58 m (190 ft). It is also evident from the plot that when the measurements were taken that ground effects are pronounced, reducing the detection distance. That is, for a radar operating in free space, the power received from a backscattering target would decay as

$$P_{\mathrm{REC}}^{\mathrm{FSPL}} \propto \frac{1}{R^4}. \tag{6}$$

However, a power regression of the data in Fig. 9 gives

$$P_{\mathrm{REC}}^{\mathrm{EPL}} = \frac{13.85}{R^{5.707}} \quad [\mathrm{mW}] \tag{7}$$

$$P_{\mathrm{REC}}^{\mathrm{EPL}} \propto \frac{1}{R^{5.707}}. \tag{8}$$

It should be noted that in (7), R is in meters.

V. Conclusion

A portable harmonic radar system for insect tracking was designed and tested. The system offers a unique combination of portability, low power output, and small tag design. The built prototype demonstrated that a tag of size 9.5 mm $\times$ 9.5 mm $(0.19\lambda_0 \times 0.19\lambda_0)$ can be detected up to 58 m (190 ft) when the unit transmits 0.1 W, uses 22 dBi transmit and receive antennas, and operates at $5.9/11.8$ GHz. Studies will be continued to investigate methods of mounting the miniaturized tag on EAB with minimal interference with movement and behavior of the insect.

References

[1] J. L. Osborne, S. J. Clark, R. J. Morris, I. H. Williams, J. R. Riley, A. D. Smith, D. R. Reynolds, and A. S. Edwards, "A landscape-scale study of bumblebee foraging range and constancy, using harmonic radar," *J. Appl. Ecol.*, vol. 36, pp. 519–533, 1999.

[2] G. P. Svensson, P. G. Valeur, D. R. Reynolds, A. D. Smith, J. R. Riley, T. C. Baker, G. M. Poppy, and C. Löfstedt, "Mating disruption in Agrotis segetum monitored by harmonic radar," *Entomologia Experimentalis et Applicata*, vol. 101, pp. 111–121, 2001.

[3] J. R. Riley and A. D. Smith, "Design considerations for an harmonic radar to investigate the flight of insects at low altitude," *Compute. Electron. Agricult.*, vol. 35, pp. 151–169, 2002, (Elsevier.).

[4] B. G. Colpitts and G. Boiteau, "Harmonic radar transceiver design: Miniature tags for insect tracking.," *IEEE Trans. Antennas Propag.*, vol. 52, pp. 2825–2832, 2004.

[5] E. A. Capaldi, A. D. Smith, J. L. Osborne, S. E. Fahrbach, S. M. Farris, D. R. Reynolds, A. S. Edwards, A. Martin, G. E. Robinson, G. M. Poppy, and J. R. Riley, "Ontogeny of orientation flight in the honeybee revealed by harmonic radar," *Nature*, vol. 403, pp. 537–540, 2000.

[6] G. Boiteau and B. Colpitts, "Electronic tags for the tracking of insects in flight: Effect of weight on flight performance of adult Colorado potato beetles," *Entomologia Experimentalis et Applicata*, vol. 100, pp. 187–193, 2001.

[7] R. D. Brazee, E. S. Miller, M. E. Reding, M. G. Klein, B. Nudd, and H. Zhu, "A transponder for harmonic radar tracking of the black vine weevil in behavioral research," *Amer. Soc. Agricult. Eng. Trans.*, vol. 48, no. 2, pp. 831–838, 2005.

[8] D. Mascanzoni and H. Wallin, "The harmonic radar: A new method of tracking insects in the field," *Ecolog. Entomol.*, vol. 11, pp. 387–390, 1986.

[9] J. Roland, G. McKinnon, C. Backhouse, and P. D. Taylor, "Even smaller radar tags on insects," *Nature*, vol. 381, pp. 120–, 1996.

[10] J. P. Gianvittorio and Y. Rahmat-Samii, "Fractal antennas: A novel antenna miniaturization technique, and applications," *IEEE Antennas Propag. Mag.*, vol. 44, no. 1, pp. 20–36, 2002.

[11] S. K. Padhi, G. F. Swiegers, and M. E. Bialkowski, "A miniaturized slot ring antenna for rfid applications," in *Proc. 15th Int. Conf. Microw., Radar Wireless Commun.*, May 2004, vol. 1, pp. 318–321.

[12] H. M. Elkamchouchi and M. N. A. El-Salam, "Square loop antenna miniaturization using fractal geometry," in *Proc. IEEE Antennas Propag. Soc. Int. Symp.*, Jun. 2003, vol. 4, pp. 254–257.

[13] C. Mahatthanajatuphat and P. Akkaraekthalin, "A double square loop antenna with modified Minkowski fractal geometry for multiband operation," *IEICE Trans. Commun.*, vol. E90-B, no. 9, Sep. 2007.

[14] G. Charvat, E. Rothwell, L. Kempel, and T. Miller, "Harmonic radar tag measurement and characterization," in *Proc. IEEE Antennas Propag. Soc. Int. Symp.*, Columbus, Ohio, Jun. 22–27, 2003.